AD-A098 086 ARTEC ASSOCIATES INC HAYWARD CALIF F/G 14/2

THERMAL NOISE EMISSIONS FROM A HOT GAS.(U)

MAR 81 D W BAUM, S P GILL, W L SHIMMIN N00014-80-C-0529

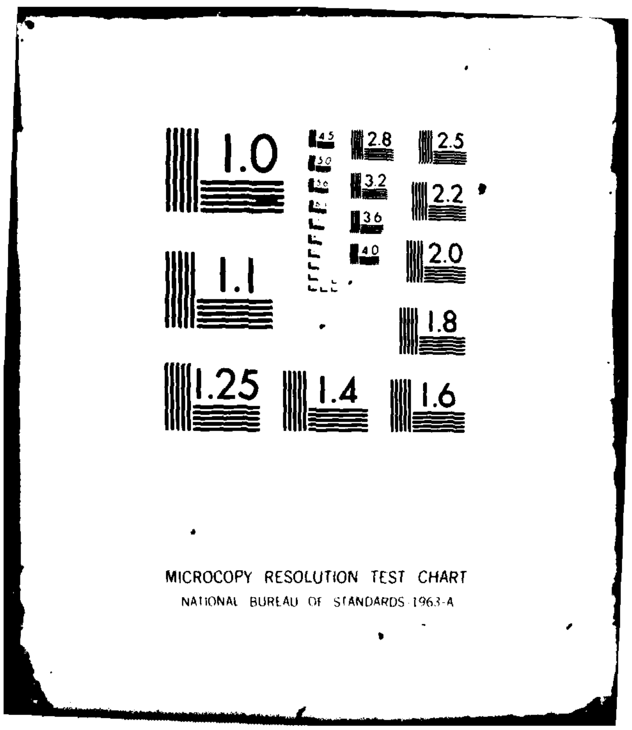
UNCLASSIFIED FR-153 NL

END

DATE FILMED

5 81

DTIC


1.0
4.5
5.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963-A

LEVEL II

12

AD A098086

ARTEC
ASSOCIATES INC

Thermal Noise Emissions
From a Hot Gas

Final Report 153

Sponsored by: Office of Naval Research
Department of the Navy
800 North Quincy Street
Arlington, Virginia 22217
Contract No. N00014-80-C-0529

Submitted by: D. W. Baum, S. P. Gill,
W. L. Shimmin, and J. D. Watson

Artec Associates Incorporated
26046 Eden Landing Road
Hayward, California 94545
Telephone: 415/785-8080

March 1981

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
Final Report 153

2. GOVT ACCESSION NO.
AD-A098 086

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
(6) Thermal Noise Emissions from a Hot Gas

5. TYPE OF REPORT & PERIOD COVERED
(9) Final rept.

6. PERFORMING ORG. REPORT NUMBER
(14) FR-[redacted]153

7. AUTHOR(s)
(10) Dennis W. Baum, Stephen P. Gill, W. Lee Shimmin, John D. Watson

8. CONTRACT OR GRANT NUMBER(s)
(15) N00014-80-C-0529

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Artec Associates Incorporated
26046 Eden Landing Road
Hayward, California 94545

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
(12) 33

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

12. REPORT DATE
(11) Mar[redacted]81

13. NUMBER OF PAGES

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
Same

15. SECURITY CLASS. (of this report)

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Thermal Noise
Temperature Measurement
Combustion Processes

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
This report describes experiments to measure thermal noise emissions from hot wire and hot gas conductors. A simple analysis of these measurements is developed to relate the thermal noise power to the thermodynamically correct temperature of the hot conductor. We conclude that the absolute temperature of the conductors can be measured to an accuracy of 1%. The results of this work suggest that non-intrusive transient temperature measurements can be made in the interior of combustion processes.

Table of Contents

1.0 Introduction

Temperature is a primary variable in combustion processes and its accurate measurement is an essential prerequisite for a proper analysis of the combustion process. Presently available electrical techniques such as thermocouples and resistance thermometers are limited in their transient response and indicate temperatures only at the thermometer surface. Optical techniques have excellent transient response but cannot measure temperature in the interior of optically thick carbon-rich flames or combustion products.

This report summarizes an effort to demonstrate the feasibility of measuring the temperature of hot gases by sensing the thermal noise power emitted by the gas.

Thermal noise or Johnson noise is the noise produced by thermal agitation of charges in a conductor. The available thermal noise power produced in a resistance is independent of the nature and the value of the resistance but is proportional to the absolute temperature and the frequency bandwidth over which the noise is measured.

Utilization of this universal property of conductors leads directly to a means of non-intrusively obtaining

transient temperature measurements in the interior of a combustion process. The measurements are thermodynamically correct even in the presence of particulate matter, flow velocity and high pressures.

Noise thermometry in solid conductors is an established measurement technique. It is used in low temperature research to measure temperatures in the millikelvin range to a high degree of accuracy (References 1 and 2). The nuclear industry employs noise thermometry to measure liquid metal temperatures to within a kelvin by immersing a conductor in the molten flow (References 2 and 3). This technique has been considered for application in fossil fuel plant process control (References 4 and 5). These measurements are usually made at low frequencies (<100 kHz) and are limited in their time response because of the thermal inertia of the probes.

The Soviets report direct measurements of acetylene-oxygen combustion flows made in the 5 to 30 MHz range and conclude that high temperature gasdynamic measurements are feasible (Reference 6). They report a frequency dependence of noise temperature measurements which was not observed in this work.

2.0 Theory of Thermal Noise

Thermal noise emitted from resistive components has long been the subject of research since it is the limiting factor for radio receiver sensitivity. The classic work by Lawson and Uhlenbeck (Reference 7) on receiver noise for World War II radars provides a clear and concise theoretical basis for noise analysis which is now an important engineering discipline.

2.1 Derivation of Thermal Noise Spectrum

The noise spectral density is a universal function of the resistance, temperature and frequency bandwidth and is derived from the fundamental laws of thermodynamics.

Consider a conductor of resistance R at temperature T. Because of the random motion of electrons there will be small fluctuations of the voltage across the ends of the conductor; the average value of the fluctuations being zero. Nyquist (Reference 8) showed that the spectrum of these voltage fluctuations is constant up to very high frequencies (at least up to 10^6 MHz) so that for all practical purposes it is a white spectrum with spectral density

given by the formula

$$\overline{v}_n^2 = G(f)\Delta f$$
$$= 4kTR\Delta f \qquad (1)$$

where R = resistance

$\overline{v}_n$ = r.m.s. voltage

T = temperature

Δf = frequency bandwidth

k = Boltzmann's constant

The proofs of this result are all based on the general principles of statistical mechanics and especially on the theorem of equipartition of energy.

Nyquist demonstrates the result for power transfer between two equal resistances at the same temperature by using transmission line theory and the equipartition of energy (Reference 7).

In a second approach a resistance R possessing a fluctuating electromotive force E(t) is connected to an ideal network made up of inductances and capacitances. By applying the equipartition theorem to the electric and magnetic energy of the network the result of equation (1) can be drived and in addition it can be proved that E(t) must be a Gaussian random process (Reference 7).

Although the fundamental result of equation (1) is independent of the mechanism of conduction it has also been derived from a specific model for the electrical conduction through a metal.

The equivalent circuit of a resistance is a thermal noise source of fluctuating voltage v_n in series with an ideal noise free resistor R. For a given amplifier input resistance R_i (assumed for now to be noise free) the thermal noise power appearing at the amplifier input is

$$P_i = \frac{\overline{v}_n^2}{R_i} = 4kT\Delta f \frac{RR_i}{(R+R_i)^2} \qquad (2)$$

Maximum input power occurs at matched impedance conditions ($R=R_i$)

$$P_{max} = kT\Delta f \qquad (3)$$

and depends only on temperature and frequency bandwidth.

2.2 Generalization of Theory

The theorem of Nyquist states the result of equation (1) in more general form by considering a two-pole linear passive network at temperature T. If the impedance between the poles is $Z = R(f) + iX(f)$ where $R(f)$ and $X(f)$ are in general frequency dependent, then it is shown that

$$\overline{v_n^2} = 4kTR(f)\Delta f \qquad (4)$$

That is, the fluctuating emf emitted by linear passive network at temperature T depends only on the real part of the network impedance.

The theorem of Williams shows that equation (4) can be derived by associating with each of the constant resistances in the network a fluctuating emf having the constant spectrum of equation (1). The result is

$$\overline{v_n^2} = 4k\Delta f|Z|^2 \sum_i \frac{R_i T_i}{|Z_i|^2} \qquad (5)$$

This can be used to predict what will happen when the different resistances are no longer at the same temperature.

2.3 Experimental Foundations of the Theory

Many experimental investigations have confirmed the basic Nyquist formula of equation (1). Wilbur (Reference 9) amplified voltage fluctuations across wire wound resistors of resistances up to about 2 megohms and compared them with fluctuations due to pure "shot" noise which is known to obey precisely the theoretical formula

$$\overline{i}_n^2 = 2eI\Delta f \tag{6}$$

where e = electronic charge

I = current

This work verified the linear dependence of G(f) on R and T from liquid air temperature to 380°K and can almost be considered as a precision measurement of Boltzmann's constant k.

The most detailed verifications of equations (4) and (5) were made by Williams (Reference 10). In one series of experiments the voltage fluctuations across two parallel resistances R_1 and R_2 at T_1 and T_2 were measured. The temperature T_2 was varied from 293°K to 743°K while R_1 remained at room temperature. The linear dependence of G(f) on T_2/T_1 and the absolute value of G(f) were well established.

In a second series a capacitance, C and inductance, L were introduced in the two branches of the circuit. Again T_2 was varied and measurements made at three different frequencies confirming that G(f) depends only on the real part of the branch impedances in accordance with equation (5).

Finally R_1, R_2 and L were kept at room temperature and the voltage fluctuations were measured as a function of capacitor temperature. The value of G(f) did not change confirming that the fluctuating emf's must be associated only with the resistance.

3.0 Experimental Results

The primary objective of the program is to experimentally verify equation (4) for solid and gaseous conductors and to demonstrate that temperature can be determined from thermal noise power measurements to a working accuracy of about 20°K in the range 1000°K to 1600°K.

3.1 Apparatus

The experimental apparatus is shown schematically in Figure 1.

The high temperature environment is provided by a $2\frac{1}{2}$-inch diameter laboratory furnace and digital setpoint potentiometric temperature controller using a chromel-alumel thermocouple. This system can maintain a 14 inch long zone in the furnace to ±1°K of the indicated temperature. The indicated temperature is monitored by direct voltage readout of the thermocouple, look up in the manufacturers conversion table and correction for room temperature variation. In this way we estimate that the temperature of the working zone of the furnace can be established to within ±2°K of actual.

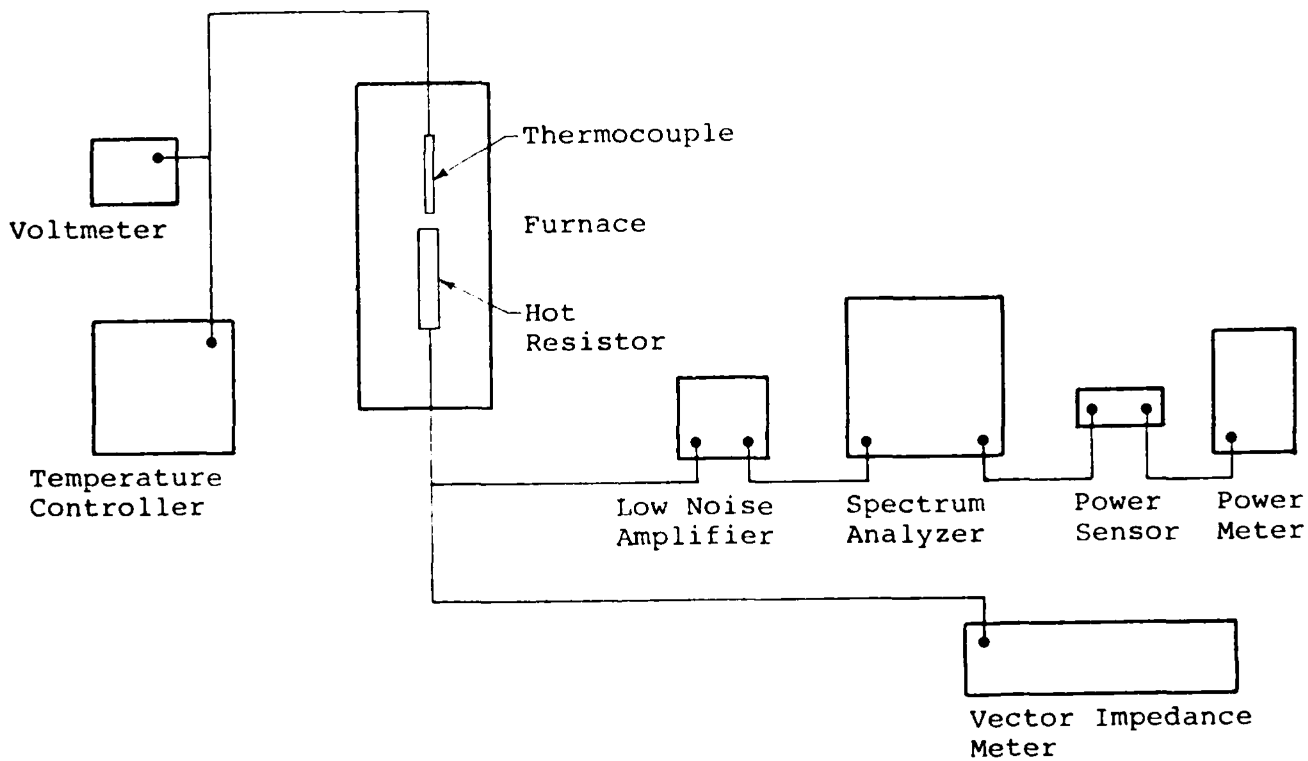


Figure 1. Schematic of the Hot Resistor Experimental Apparatus

An 8 inch long 1-3/4 inch diameter cylindrical housing (Figure 2) made of Inconel is used to electromagnetically isolate the hot resistor from external r.f. interference. The housing, Inconel electrical leads and alumina-silica insulating material are all capable of withstanding the maximum furnace temperature of 1600°K.

In the wire resistor experiments a 1 mil Stablohm (70 Ni 30 Cr) wire was attached from the center lead-in to the grounded housing (Figure 2). In the gas resistor experiments, the air in the annulus between the housing and the center lead-in was seeded with cesium chloride to provide a reistance somewhere between 100 and 10,000 ohms depending on the temperature and vapor pressure of the cesium chloride.

In a 1 MHz bandwidth the maximum available thermal noise power ranges from 4×10^{-15} watts to just over 10^{-14} watts for the 300 to 1600°K range (Equation 2). These very small power levels can be readily and accurately measured using standard r.f. noise measuring equipment. In the present experiments, the noise from the hot resistor is input into a low noise amplifier which amplifies the signal by 40dB. The signal is then passed onto a spectrum analyzer mainframe which provides a high quality bandpass filter centered at a selected frequency and

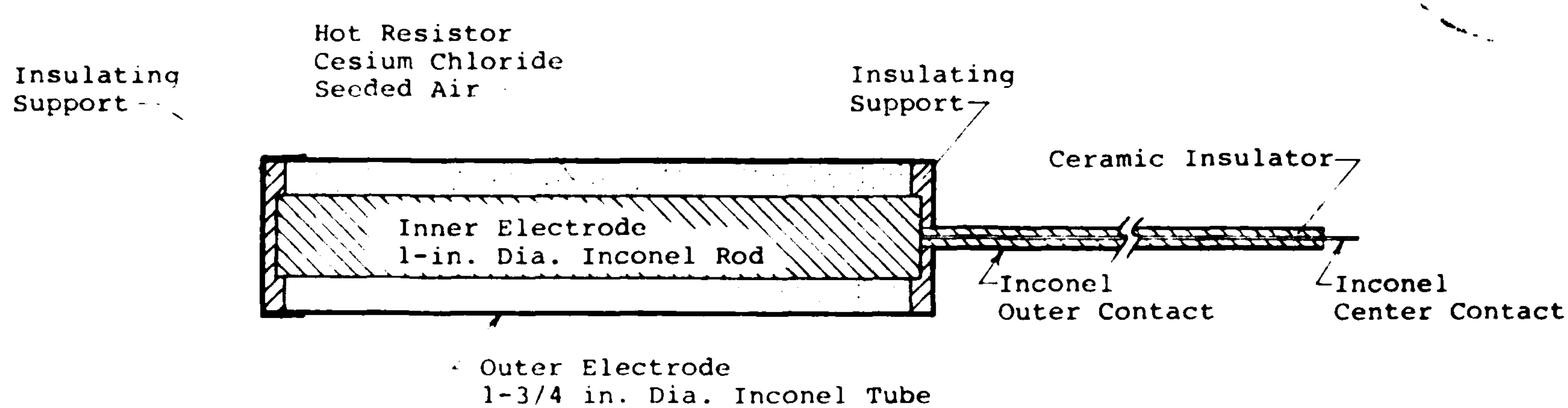


Figure 2. Schematic of Housing for Hot Resistor Experiments

then adds another 50dB signal amplification. The output from the spectrum analyzer is a 21.4 MHz signal directly proportional to the filtered input power. This output is sent to a thermistor power sensor which is monitored by a power meter with meter movement readout.

A vector impedance meter with meter movement readout is used to determine impedance magnitude and phase for the hot resistor experiment and the amplifier/power measuring system.

The measurement electronics were allowed to warm up up for at least two hours to minimize drift in the calibration settings. Prior to taking noise power measurements, the calibrations of the spectrum analyzer, power meter and vector impedance meter were carefully checked and noted. We estimate that with this procedure power measurements are accurate to about 1%, with most of the error attributable to reading the meter movement.

One of the largest sources of potential error in these experiments is the possible difference in temperature between the location of the thermocouple and the interior of the cylindrical housing. To eliminate this difference we allowed the cylinder to remain at temperature for over 30 minutes until we perceived no change in measured power or source impedance.

3.2 Data Analysis Techniques

The simplest equivalent circuit of the measurement system is shown in Figure 3. In general the impedance of the temperature source Z_s is not matched to that of the low noise amplifier Z_L. Furthermore the thermal noise emitted by the input of the low noise amplifier must be taken into account.

The response of the amplifier can be represented by the set of linear equations

$$
\begin{aligned}
v_1 &= A_{11} i_1 + A_{12} i_2 + A_{13} \\
v_2 &= A_{21} i_1 + A_{22} i_2 + A_{23}
\end{aligned}
\qquad (7)
$$

By experiment we determined that v_1 is independent of i_2 and that the power sensor is a constant load. Thus $A_{12} = 0$ and $i_2 = v_2/_R$

Thus equation (7) can be rewritten

$$
\begin{aligned}
v_1 &= Z_L i_1 + v_L \\
v_2 &= Z_T i_1 + v_{OC}
\end{aligned}
\qquad (8)
$$

We consider that v_{OC} is comprised of internal amplifier electronic noise v_A and amplifier input thermal noise v_L

$$v_{OC} = v_A + Av_L \qquad (9)$$

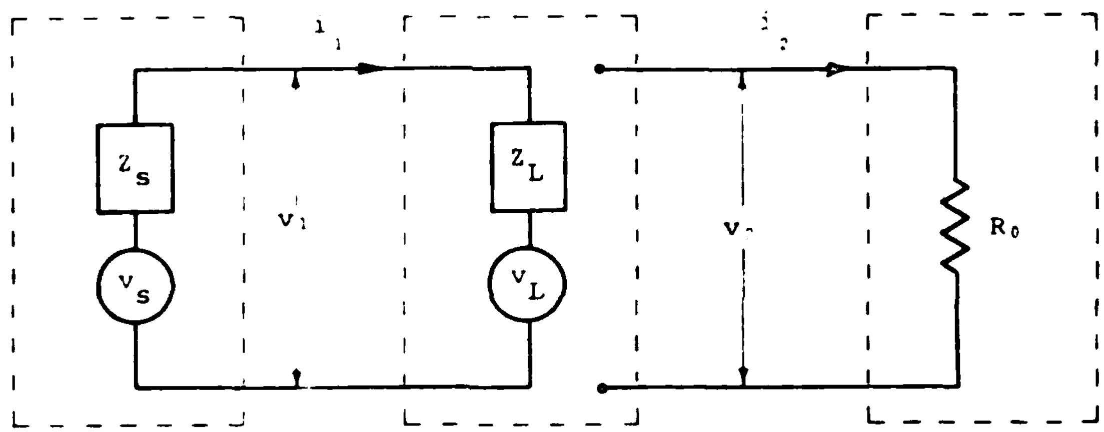


Figure 3. Equivalent Circuit of Thermal Noise Source and Linear Amplifier

From the general input circuit (Figure 3) the current i_1 is

$$i_1 = \frac{v_s+v_L}{Z_s+Z_L} \tag{10}$$

where
$$\overline{v}_s^2 = 4kT_sR_s\Delta f \tag{11}$$
$$\overline{v}_L^2 = 4kT_LR_L\Delta f$$

Combining (8), (9), (10) and (11)

$$P = \frac{\overline{v}_2^2}{R_o}$$

$$= \frac{4k\Delta fGT_sR_sR_L}{|Z_s+Z_L|^2} + 4k\Delta fGT_LR_L^2\left|\frac{1}{Z_s+Z_L} + \frac{A}{Z_T}\right|^2 + P_A \tag{12}$$

where $P_A = \frac{\overline{v}_A^2}{R_o}$

and $G = \frac{|Z_T|^2}{R_oR_L}$

In our experiments we measure P, R_s, R_L, Z_s, Z_L. The values of k and Δf are known. The unknowns in addition to the source temperature T_s are therefore $\frac{A}{Z_T}$, G, T_L, and P_A. It should be restated here that R_s and R_L are the real parts of the source and input impedances and are in general frequency dependent.

To determine the unknowns we adopted the following procedure. First we measured power for several calibrated source conditions including open circuit, short circuit, pure capacitive, pure inductive and several calibrated pure resistive room temperature terminations. These source calibration data gave us reasonably accurate values for the 4 amplifier unknowns.

We then used equation (12) and the measured power from the hot resistor experiments to calculate the hot resistor temperature, T_s. These calculated temperatures are all within 3.3% of the indicated temperatures measured by the thermocouple and most of the data is within 1%. This was the highest accuracy for correlating the data that we could achieve without using a calibrated broad band noise source with an "equivalent temperature" of several thousand Kelvins.

The most important amplifier parameter is the gain, G since it appears in two of the terms of equation (12). The most accurate value of gain would best be determined by using an "equivalent high temperature" calibrated noise source along with our calibrated reactive and room temperature resistive sources.

3.3 Final Results

The variation of noise power with frequency bandwidth Δf is shown in Figure 4. This data was taken with wound wire resistors of about 160 ohms for two temperatures, 730°K and 1230°K and verifies the linear dependence of noise power on bandwidth.

The linear dependence of noise power on resistor temperature is shown by the nickel-chromium wire data in Figure 5. In these tests a wound wire resistor of about 75 ohms was used and noise power was measured in a 3 MHz bandwidth centered at 20 MHz. Figure 6 shows the calculated temperature based on measured noise power versus the measured thermocouple temperature. Figure 7 shows the calculated noise power based on measured thermocouple temperature versus the measured noise power. These correlations were made using equation (12). The calibration data and amplifier constants are presented in Table 1. The measured hot wire data is given in Table 2.

The source impedance of the hot wire experiments is complex because of the capacitance and inductance of the housing and electrical leads. However the magnitude and phase of the source impedance were constant to within 4% during the experiment.

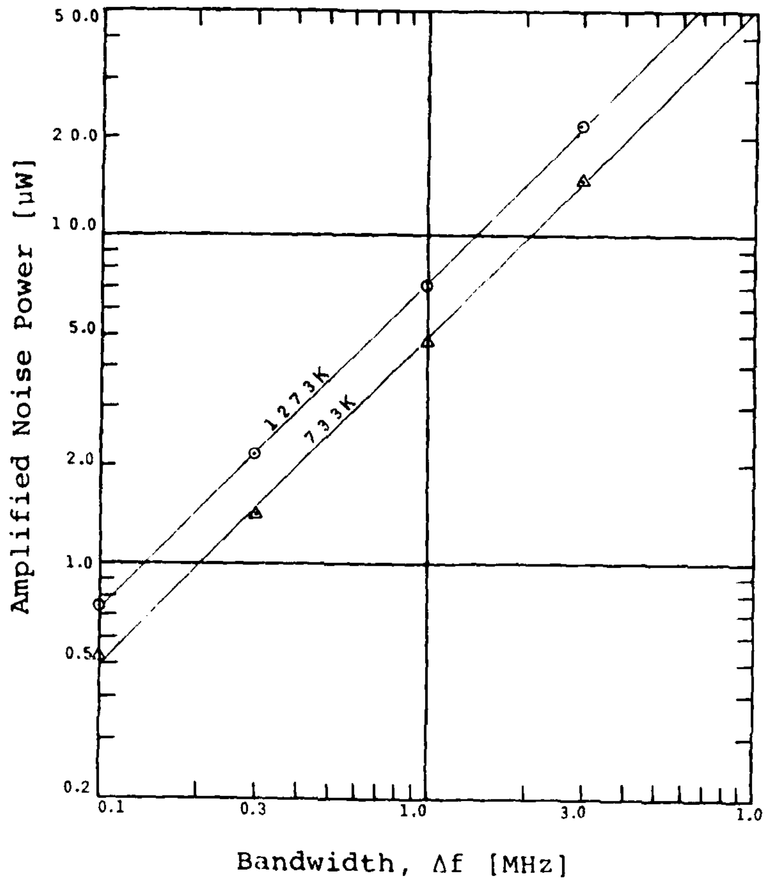


Figure 4. Noise Power from Hot Wire Resistor versus Bandwidth

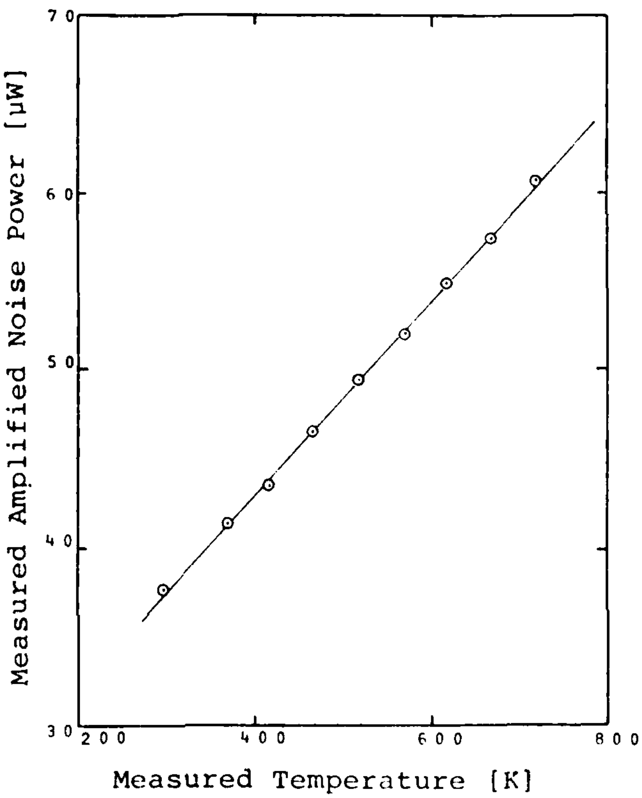


Figure 5. Plot of Measured Amplified Noise Power versus Measured Hot Wire Resistor Temperature

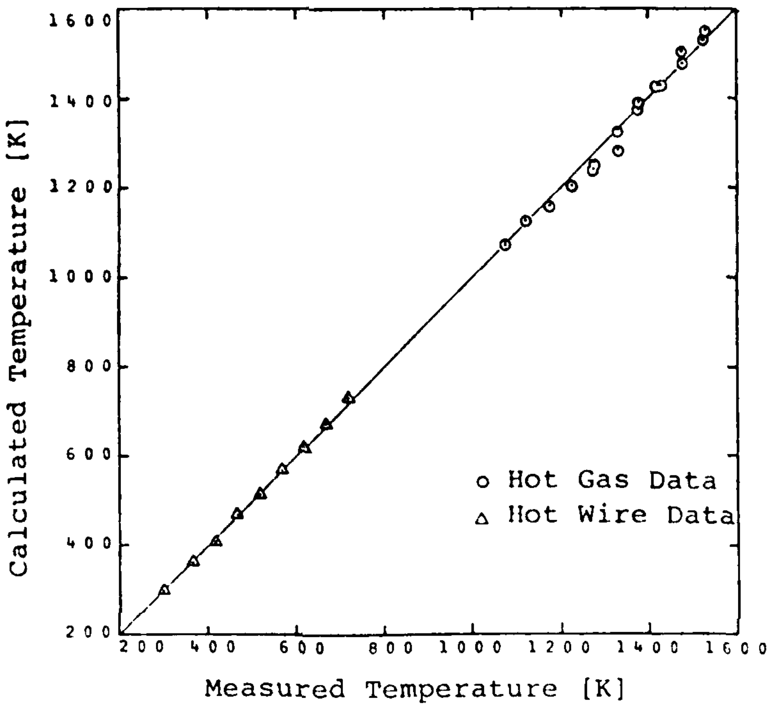


Figure 6. Calculated Temperature versus Measured Temperature for Hot Wire and Hot Gas

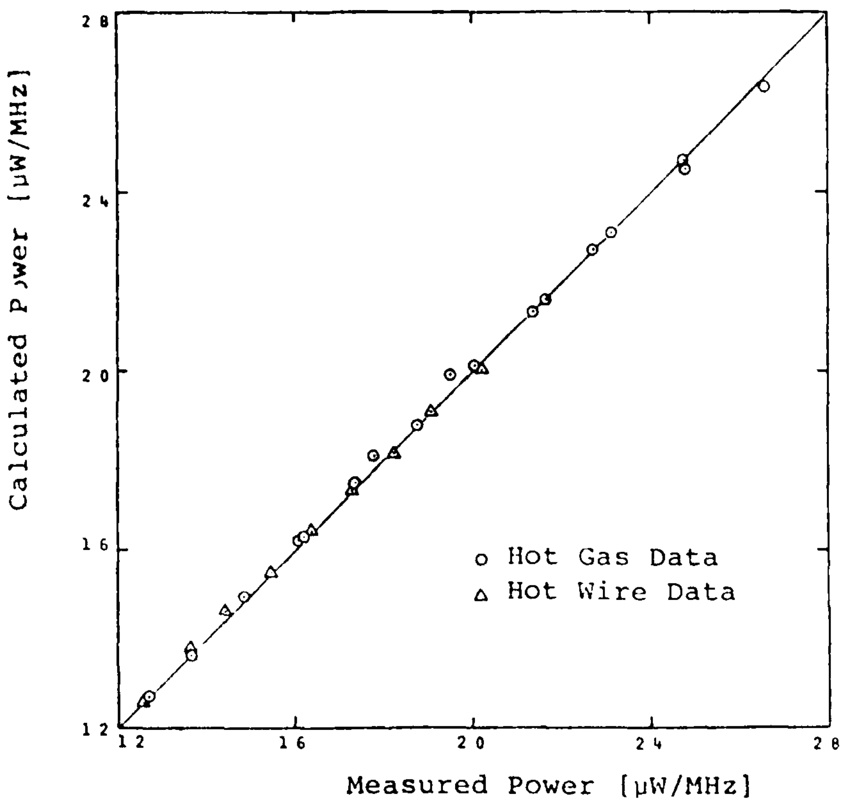


Figure 7. Plot of Calculated Noise Power versus Measured Noise Power Normalized to Unit Bandwidth (in Megahertz)

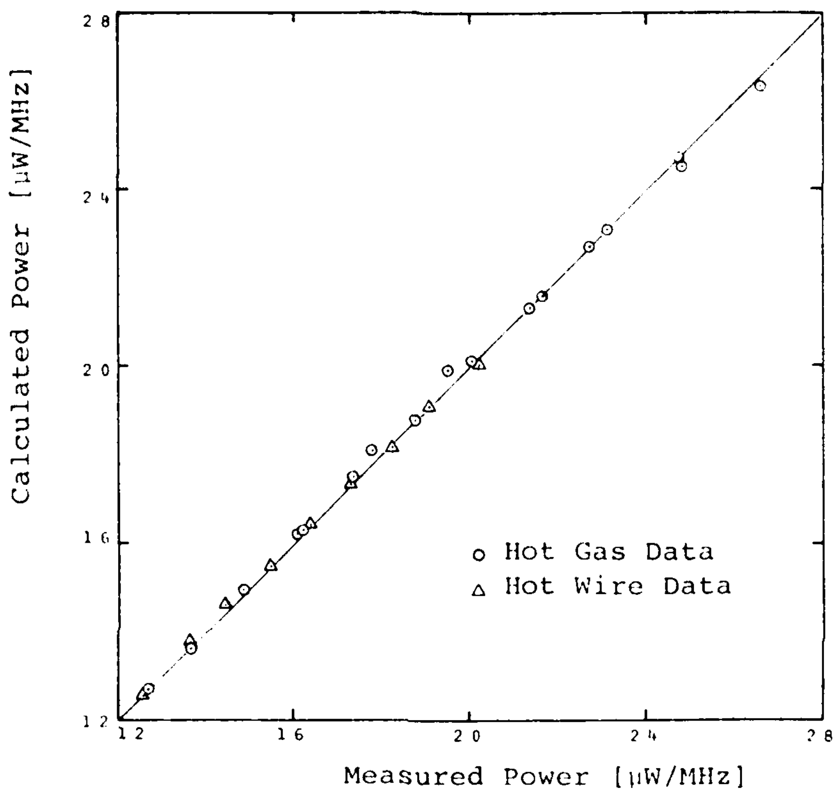


Figure 6. Plot of Calculated Noise Power versus Measured Noise Power Normalized to Unit Bandwidth (in Megahertz)

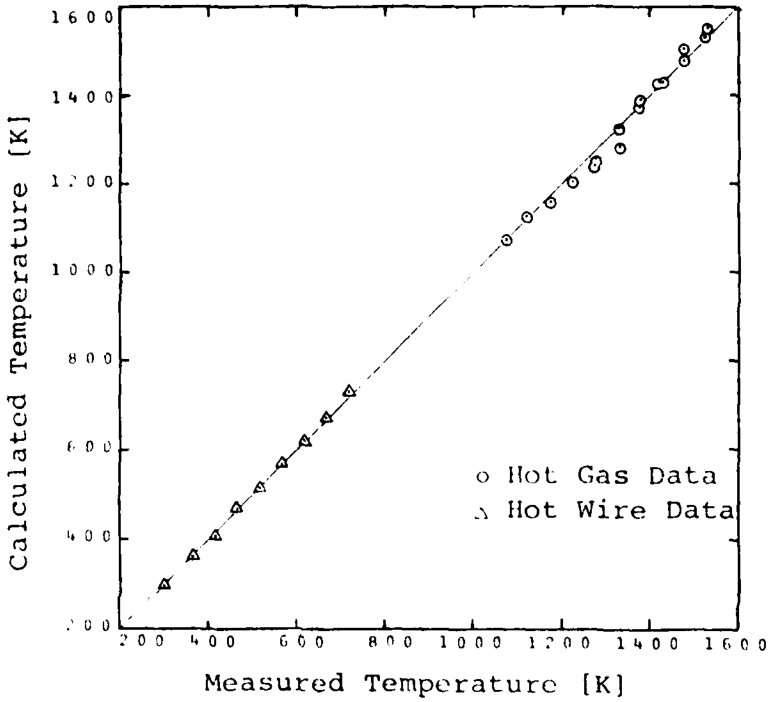


Figure 7. Calculated Temperature versus Measured Temperature for Hot Wire and Hot Gas

Calibration Data $T = 292°K$

Source	Impedance Magnitude (ohms)	Impedance Phase (degrees)	Noise Power (μwatts)
Open Circuit	∞	Ø	31.8
Short Circuit	Ø	Ø	28.4
Capacitor	94	-90	30.7
Inductor	37.9	90	31.0
50 ohm	50	.2	37.4
75 ohm	75	Ø	37.2
600 ohm	543	-23.8	33.4

Amplifier Constants

Impedance Magnitude	44.2	ohms
Impedance Phase	3.5	degrees
Gain	91.1	dB
Frequency	20	MHz
Δf	3	MHz
$\frac{A}{Z_T}$ Magnitude	.01245	siemens
$\frac{A}{Z_T}$ Phase	183	degrees
P_A	22.02	μwatts
T_L	148.5	°K

Table 1. Hot Wire Resistor Calibration Data and Amplifier Constants

Impedance* Magnitude (ohms)	Impedance* Phase (degrees)	Measured Noise Power (μwatts)	Measured Thermocouple Temperature (°K)	Calculated Power (Equat. 12) (μwatts)	Calculated Temperature (Equat. 12) (°K)
45.5	-17.5	60.7	719	59.9	734
45.5	-17.5	57.4	667	57.2	671
45.5	-17.5	54.8	617	54.6	621
45.5	-17.5	51.9	568	52.0	566
45.5	-17.5	49.2	517	49.3	515
45.5	-17.5	46.5	464	46.5	463
45.5	-17.5	43.4	416	44.0	404
45.5	-17.5	41.2	369	41.6	362
45.5	-17.5	37.7	298	37.8	296

* The complex impedance was not monitored during these early experiments and is assumed constant. The d.c. wire resistance varied from 74.4 to 77.9 ohms during the experiment.

Table 2. Hot Wire Resistor Data

In the hot gas experiments however the source impedance varies considerably and the data does not correlate well unless impedance mismatch effects between source and amplifier are accounted for properly as in equation (12).

The results of the hot gas experiments are shown in Figures 6 and 7. In these tests the heated air seeded with cesium chloride formed the resistor. Noise power was measured in a 1 MHz bandwidth centered at 20 MHz. The calibration data and amplifier constants are given in Table 3. The measured hot gas data is found in Table 4.

The cesium chloride air resistor is a highly corrosive agent on the Inconel surface of the housing and electrodes. In our first experiments the surfaces of the electrodes were fresh. In subsequent tests the walls were coated with a heavy scale of precipitated cesium salts. However this did not affect the quality of the data. The scale changes the capacitance of the source but as predicted by the theorem of Nyquist, only the real part of the source impedance contributes to the thermal noise.

Calibration Data T = 296°K

Source	Impedance Magnitude (ohms)	Impedance Phase (Degrees)	Noise Power (μwatts)
Open Circuit	∞	Ø	10.15
Short Circuit	Ø	Ø	10.4
Capacitor	92.4	-90	9.8
Inductor	37.9	90	10.85
50 ohm	50	.2	12.6
75 ohm	75	Ø	12.55
600 ohm	543	-23.8	10.85

Amplifier Constants

Impedance Magnitude	50.7	ohms
Impedance Phase	9.6	degrees
Gain	90.71	dB
Frequency	20	MHz
Δf	1	MHz
$\frac{A}{Z_T}$ Magnitude	.00993	siemens
$\frac{A}{Z_T}$ Phase	188	degrees
P_A	7.74	μwatts
T_L	144	°K

Table 3. Hot Gas Resistor Calibration Data and Amplifier Constants

Impedance Magnitude (ohms)	Impedance Phase (degrees)	Measured Noise Power (μwatts)	Measured Thermocouple Temperature (°K)	Calculated Power (Equat.12) (μwatts)	Calculated Temperature (Equat.12) (°K)
84.8	-54.1	26.6	1528	26.3	1552
88.7	-58.0	24.8	1477	24.5	1505
92.4	-60.2	23.15	1423	23.1	1428
97.0	-63.0	21.7	1375	21.6	1388
102.5	-66.2	19.55	1327	19.9	1283
108.5	-70.0	17.8	1276	18.1	1237
114.0	-73.8	16.2	1223	16.3	1206
119.0	-76.5	14.9	1175	15.0	1157
123.5	-79.4	13.7	1121	13.7	1127
128.0	-81.4	12.75	1074	12.8	1071
86.6	-59.6	24.75	1525	24.7	1529
89.3	-64.0	22.7	1474	22.7	1477
93.2	-66.0	21.4	1422	21.3	1432
97.0	-67.9	20.05	1376	20.1	1372
102.2	-69.8	18.8	1325	18.8	1325
106.5	-72.0	17.35	1275	17.5	1251
112.0	-74.2	16.1	1224	16.3	1199

Table 4. Hot Gas Resistor Data

4.0 Conclusions

The primary objective of this work is to demonstrate that the temperature of hot gases such as combustion products can be determined from thermal noise power measurements. This objective was successfully met and we have concluded that the absolute temperature can be determined to within 1% when the parameters of the amplifying system are known to at least this accuracy.

This temperature sensing method can be used to measure quasi-steady flows with response times of about 0.1 sec with currently available instrumentation. Accurate submicrosecond transient measurements should be possible with an amplifying system based on a Schottky diode for sensing noise power.

References

1. R. J. Soulen, R. P. Gifford, "Josephson-Effect Absolute Noise Thermometer," Journal Applied Physics, Vol. 32, June 1978.

2. H. G. Brixy, "Noise Thermometry," Kerntechnik (Germany), Vol. 15, No. 10, Julich, West Germany, October 1973.

3. C. J. Borkowski, T. V. Blalock, "A New Method of Johnson Noise Thermometry," Rev. Sci. Instrum., Vol. 45, No. 2, February 1974.

4. J. F. Schooley, "State-of-the-Art Instrumentation for High Temperature Thermometry," Proceedings of 1977 Symposium on Instrumentation and Process Control for Fossil Demonstration Plants, Chicago, July 1977.

5. R. A. Kemper, "Survey of Noise Thermometry," Proceedings of Symposium on Temperature, Its Measurement and Control in Science and Industry (5th), Washington, D.C., June 1971.

6. Yu. S. Ivashchenko, Yu. G. Korobchencko, T. S. Bondarenko, "Measurement of the Noise Temperature of a Plasma of Combustion Products Using a Contactless Capacitive Converter," Siberian Institute of Technology, Krasnoyarsk, USSR, December 1976.

7. J. L. Lawson and G. E. Uhlenbeck, "Threshold Signals," MIT Radiation Laboratory Series, McGraw-Hill (1950).

8. H. Nyquist, Phys. Rev. 32, 110 (1928).

9. D. A. Wilbur, "Thermal Agitation of Electricity in Conductors," Dissertation, U. of Mich., (1932).

10. F. C. Williams, J.I.E.E., 81, 751, (1937).

DATE
FILMED

8